Transmission Expansion Planning Considering Conductor Proposals with Different Wire Size and Technology

Andrés H. Domínguez, Antonio Escobar Z., Ramón A. Gallego
Department of Electrical Engineering
Technological University of Pereira, Pereira, Colombia
ahdominguez@utp.edu.co, aescobar@utp.edu.co, ragr@utp.edu.co

Abstract**—In this article a model and a solution methodology is presented to solve the transmission network expansion problem, considering the selection of the wire size and the construction technology of the conductors for transmission lines for each new right-of-way. The optimization problem is solved using a specialized genetic algorithm that uses the logic of the Chu-Beasley Genetic Algorithm combined with an exact technique. The methodology is tested in the Colombian electric system of 93 buses and 155 candidate lines, which is modified in order to allow investment options for the selection of the conductors. The results obtained improve the traditional solution for the Colombian electrical system in the transmission planning study.**

Index Terms**— Genetic Algorithm, High-Temperature Low-Sag Conductor (HTLS), Optimization, Transmission Planning.**

I. INTRODUCTION

The traditional electrical energy transmission network expansion problem determines the new investments in transmission lines and substations. The new investments must allow a suitable electrical energy flow transfer between different locations in the power system taking into account both current and future operation. The features of the investment options are high costs, the long construction periods and the long time recovery of investment. The planning studies take the current system as benchmark and considering an increased demand in the buses of the system, also alternatives in new power units, upgrade existing power units, and all foregoing in a horizon time of 10 year or more. The static planning determines the minimum cost solution from a mathematical optimization problem approach that considers the current network like part of the future solution, i.e., in the solution of the problem is not permitted removing, moving or unconnecting in a permanent way, the elements that are operating in the current network. The electrical energy transmission system expansion planning problem is a mixed integer nonlinear programming problem, and is NP-complete, that is, a problem for which no method exists that solves it in polynomial time. This problem presents a large number of local optimal solutions and is not convex. The problem is not solving successfully using exact optimization techniques when system size becomes large, and the system has an appreciable amount of buses isolated, because the number of solutions grows exponentially. In other way, when the size system is small or medium sized, the optimal solution is found using techniques like Branch and Cut or Branch and Bound [1, 2]. In this cases, it is found that the computer systems require great amount of computational time when is compared with the time required by metaheuristic's techniques like Tabu Search (TS) or the Genetic Algorithm proposed by Chu and Beasley (GACB) [3, 4, 5, 6]. The problems that are both PNLEM and NP-complete are the most difficult to solve. To solve the transmission planning problem several solution methodologies have been used ranging from the heuristic techniques and exact methods to metaheuristic techniques. Specialized literature reports several mathematic models that have been used to solve the planning problem in [7, 8]. In [9] is found a planning types summary. In [10] is presented a rating of the algorithms mostly used. On the other hand, several researches that include the transmission planning problem are found in [11].

In this paper is presented a solution methodology that alter the traditional model used to solve the static transmission expansion planning problem, we consider new alternatives of different wire size and construction technology of the conductors for transmission lines that belong to the set of all new routes. The idea is to take advantage of new conductors manufacturing technologies to increase the transmission capacity. When the ACSR conductors are replaced for high temperature and low sag conductors (HTLS) that utilize similar mechanical structures, can take advantage of economies of scale. The Chu-Beasley Genetic Algorithm is used as solution method, which in its codification broken up into two parts the analysis. In the first part is defined what, where and how many new equipment must be installed in an electric system, and in the second phase the conductor type is selected that should be used in each transmission line in the system. The solution obtained after the optimization process should ensure the suitable operation in a future generation-demand for a long-term scenario. In this paper the 93-bus Colombian system and 155 right-of-ways is taken as benchmark, which is modified to take into account the HTLS conductors in the investment proposals of the new transmission lines. The results obtained show a strong trend toward the investment in HTLS conductors with values lower than those determined in previous studies.

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II. MATHEMATICAL FORMULATION OF THE PLANNING PROBLEM

In this section a mathematical formulation is presented to solve the static planning problem based on conductor proposals with different wire size and technology. This model is derived from DC model [11], which is considered ideal to transmission planning studies.

$$min = \sum_{(i,j)\in\Omega_2} C_{ij} n_{ij} + \sum_{(i,j)\in\Omega_3} C''_{ij} n''_{ij} + \alpha \sum_{i\in\Omega_1} r_i \qquad (1)$$

Subject to:

$$S^0 f^0 + S' f' + g + r = d \qquad (2)$$

$$f^0_{ij} - (\theta_i - \theta_j)(n_{ij} + n^0_{ij})\gamma_{ij} = 0 \quad \forall (i,j) \in \Omega_2 \qquad (3)$$

$$f'_{ij,k} - (\theta_i - \theta_j) n'_{ij,k} \gamma'_{ij,k} L_{ij,k} = 0 \quad \forall (i,j) \in \Omega_3, k = 1,\ldots,nk \qquad (4)$$

$$\sum_{k=1}^{nk} L_{ij,k} = 1 \ \forall (i,j) \in \Omega_3 \qquad (5)$$

$$\left|\theta_i - \theta_j\right| \le \frac{\overline{f_{ij}}}{\gamma_{ij}} \quad \forall (i,j) \in \Omega_2 \qquad (6)$$

$$\left|\theta_i - \theta_j\right| \le min\left\{\left(\frac{\overline{f_{ij,1}}'}{\gamma'_{ij,1}} + M(1 - L_{ij,1})\right), \ldots, \left(\frac{\overline{f_{ij,nk}}'}{\gamma'_{ij,nk}} + M(1 - L_{ij,nk})\right)\right\} \forall (i,j) \in \Omega_3 \ (7)$$

$$0 \le g \le \overline{g} \qquad (8)$$

$$0 \le n_{ij} + n^0_{ij} \le \overline{n_{ij}} \qquad (9)$$

$$0 \le n''_{ij} \le \overline{n_{ij}} \qquad (10)$$

$$0 \le r \le \overline{r} \qquad (11)$$

$$n''_{ij} = \sum_{k=1}^{nk} n'_{ij,k} L_{ij,k} \qquad (12)$$

$$C''_{ij} = \sum_{k=1}^{nk} C'_{ij,k} L_{ij,k} \qquad (13)$$

$$L_{ij,k} \in \{0,1\},\ \{\mathrm{n}_{ij}, n^0_{ij}, n'_{ij,k}, n''_{ij}\} \ \text{Integer}$$

$$\{\gamma_{ij}, \gamma'_{ij,k}\} \qquad \text{Discrete}$$

$$\{f^0_{ij}, f'_{ij,k}, g_i, \theta_j\} \qquad \text{Unbounded}$$

In the previous model, C_{ij} is the cost of a circuit in the *i-j* branch that belong to existing path; $C'_{ij,k}$ is the cost of a circuit with conductor type *k* in the *i-j* branch that belong to new network; Ω_1 is the set of demand buses; Ω_2 and Ω_3 represent the set of existing and new right-of-ways, respectively; *α* is a parameter that penalizes the load shedding; *r* represents the load shedding vector; S^0 and S' are the node-branch incidence matrices of the power system for the base case and the new network, respectively; f^0 and f' are flow power vectors, where an element in f^0 (f_{ij}^0) represents the total flow in the *i-j* branch for the base case, and an element in f' ($f'_{ij,k}$) represents the total flow in the *i-j* branch for the new network in the conductor type *k*; *g* is a vector with g_i elements (generation in bus *i*) whose maximum value is $\overline{g}$, a variable with an upper line represents the maximum limit of this variable; *d* is the demand vector, γ_{ij} is the susceptance associated to one circuit in the *i-j* branch for the base case; $\gamma'_{ij,k}$ is the susceptance associated to one circuit in the *i-j* branch for the new network, in the conductor type *k*; θ_i is the phase angle in bus *i*; n^0_{ij} is the number of circuits in the *i-j* branch for the base case; n_{ij} is the number of circuits added in the *i-j* branch for the base case; $n'_{ij,k}$ is the number of circuits added in the *i-j* branch for the new network, with conductor type *k*; and $L_{ij,k}$ is a binary variable that allow select the conductor type *k* in the *i-j* branch. The objective function consists of three components: The first one represents the total cost of the investments made in existing paths, the second one represents the total cost of the investments made in the new network, and the third one represents the penalization for the total load shedding. In the model it is necessary to make the following clarifications: 1) *M* is a parameter that is defined before the optimization process start. It establishes a control in the second Kirchhoff's law for the angular aperture limits. 2) The constraints set in equation 4 represents Kirchhoff's second law applied on each new right-of-way, between the *i-j* buses that use a conductor type *k*. If the conductor type *k* is selected in the *i-j* branch, then $L_{ij,k}=1$, and the Kirchhoff's second law is applied. If $L_{ij,k}=0$ the Kirchhoff's second law is not applied, additionally, the variable $f'_{ij,k}$ is forced to take cero value. 3) Constraint 5 ensures that for each new transmission line only one type of conductor within all *nk* available can be selected. 4) There are two types of constraints associated to angular aperture defined in the equations system. The first one is applied to base case or existing network and it has the traditional form (equation 6). The second one is applied only to new right-of-ways. It contains the term $M(1-L_{ij,nk})$. When $L_{ij,ck}=1$, the constraint is defined as follows:

$$\left|\theta_i - \theta_j\right| \le \overline{f_{ij,ck}}' / \gamma'_{ij,ck} \qquad (14)$$

Constraint 14 for the *i-j* right-of-way and conductor type *k*. Then, if *Lij,k=0*, the constraints set in equation 7 is not generated for the conductor type *k*. 5) The equations system that is presented does not consider modifying the conductor type in the existing transmission network.

III. HIGH – TEMPERATURE LOW-SAG CONDUCTORS

The high-temperature low-sag conductors (HTLS) have higher current capability than conventional conductors. They can operate at high temperatures with low rates of thermal expansion, allowing them to carry a biggest power flow. In other way, when the HTLS conductors are considered in a network for their employment, they can conserve the same installation distance between conductors, additionally the distance between conductors and the surrounding vegetation along the span of the transmission line is conserved too, all foregoing when is compared with conventional conductors [12,13,14]. The HTLS conductors have a high strength core consisting of steel, steel alloy, or a composite material surrounded by multiple layers of aluminum or aluminum alloy. Unlike conventional conductors, the aluminum wires of the HTLS conductors must have stable electrical and mechanical properties at temperatures between 200 and 250 degrees celsius. If the HTLS conductors are compared to a conventional conductor as the called ACSR (Aluminum Conductor Steel Reinforced), with equal diameter, the HTLS conductors present a capacity of current between 1.4 and 2 times higher. Two typical HTLS conductors are as follows:

a. ACSS (Aluminium Conductor Steel Suported): It consists of fully annealed aluminum wires stranded over a core of high strength steel (or extra high strength steel). Its installation is easy; however in the installation process extra care should be take because its construction consists of annealed aluminum. The operating temperature is close to 200°C, and in the cases where the core is coated by a layer of aluminum can reach 260°C. On the other hand, when the conductor is galvanized it can operate at 245°C. The stringing method is the same as ACSR conductors, and its possibility of failure by fatigue is minimum. The ACSS construction specifications are found in the international standards ASTM (American Society for Testing and Materials) B856 y B857.

b. ACCR (Aluminum Conductor Composite Reinforced): it consists of aluminum-zirconium alloy over a reinforcing core of ceramic fibers in an aluminum matrix that improves its conductivity. The continuous operating temperature is 210°C and when an emergency regimen is presented the operating temperature increases up to 240°C. The ACCR construction specifications are found in the international standard ASTM B976. The installation method is similar to conventional ACSR, however in the installation process care should be take not to bend or break the ceramic fibers. The Installation time is 10% higher than ACSR conductor.

Another types of HTLS conductor are listed below: (Z) TACIR (Super-Thermal Resistant Aluminum Alloy Conductor, Invar Reinforced), G(Z)TACSR (Gap-type Super-Thermal Resistant Aluminum Alloy Conductor, Steel Reinforced) and ACCC (Aluminum Conductor Composite Core) [13,14]. In Table I a relative cost of the HTLS conductors with their accessories and installation respect to ACSR conductors [14] is presented.

TABLE I. RELATIVE COST OF THE HTLS CONDUCTORS (CABLE, ACCESSORIES AND INSTALLATION) RESPECT TO ACSR.

Conductor type	ACSR	ACSS	GZTACSR	ZTACIR	ACCC	ACCR
relative cost	1	1.1-1.5	2	3.5	5-7	10

IV. THE PROPOSED METHODOLOGY

In this paper, the mathematical optimization technique analyzes a bigger space of solutions than in the traditional planning problem. This is because each candidate circuit in the new network has different alternatives in conductor types. For the new network, the methodology selects the circuits in each *i-j* branch with the conductor that minimizes the global investment for a future generation-demand scenario. In the traditional planning, the type of conductor in each new transmission line is an input data for the optimization process. This leads to suboptimal solutions. A relevant aspect is that HTLS conductors can be proposed with greater power flow transport capacity, only ensuring a similar ACSR diameter, for a given *i-j* branch. Other advantages are the use of the same structures, and the use of the same of the equipment needed in the installation process.

In a new project, about 30% of the total cost of a transmission line is associated with the wire. Taking into account the relative cost of the ACSS respect to ACSR, for a cost ratio between the wires of 1.5, the increase in the total cost of the transmission line is 15%. Accordingly, the optimal solution obtained using HTLS conductors can be better that the solution obtained with ACSR conductors. Also it is interesting in the cases which only one circuit with a HTLS conductor they allow transporting the same power than two circuits with conventional conductors. The decision of using or not the HTLS conductors is left to optimization process, where several proposals of conductor types exist for each new right-of-way.

To consider the replacement of a conventional conductor by a HTLS conductor, the following conditions must be met: 1) for a given transmission line, the HTLS conductor must present a lower or equal thermal elongation rate than a conventional conductor operating at a lower temperature. 2) The Maximum horizontal mechanical stress of the HTLS conductor should not exceed more than 10% of conventional conductor (to avoid changes in structures and foundations). 3) The HTLS conductor should have high mechanical self-damping. 4) The HTLS conductor should have same or smaller outside diameter respect to conventional conductor (to avoid changes in structures and other network elements). 5) The resistance of the HTLS conductor should be same or smaller than the resistance of conventional conductor (to reduce electrical losses) [14].

The use of the HTLS conductors encourages the research of the transmission expansion planning problem, due to economies of scale that can take advantage of their use. In 1998, the international council on large electric systems (CIGRE) made a survey about the conductors used in some countries, with the purpose to obtain networks with enough power capacity into future. The survey results show than a grand part of the networks (close to 82%) are built with ACSR conductors [15]. Therefore, it is interesting inquire into the convenience of take the HTLS conductors within future investment alternatives.

In this research, a specialized Chu-Beasley Genetic Algorithm (GACB) selects the best subset of transformers, the transmission lines and conductors type. The components that conform the GACB are described in the following items:

A) Codification: The proposed codification has two parts. In the first part, the specialized GACB should determine the circuits that must be added. In the second part, for each new transmission line, it should determine the conductor type. The Fig. 1 presents the codification scheme used.

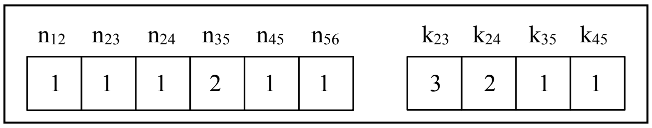

Fig. 1. Codification proposed in the methodology.

In Fig. 1, n_{12} and n_{56} represent the transformers that are added. n_{23}, n_{24}, n_{35} and n_{45} represent transmission lines that are added. k_{ij} represents the conductor type proposal for a transmission line. For example, in the line 2-3 is selected the conductor type 3 (k_{23}=3), in the line 2-4 is selected the conductor type 2 (k_{24}=2), in the line 3-5 is selected the conductor type 1 (k_{35}=1) and in the line 4-5 is selected the conductor type 1 (k_{45}=1). In the database is relates each conductor type with its specification data.

B) Initial Population: The initial population of the genetic algorithms is generally constructed in randomly form. These solutions can be improved heuristically. The initial population is constructed in randomized controlled way and includes criteria of sensitivity in the process. A summary of the most common techniques to build the initial population can be found in [16]. Building a part of the initial population using constructive heuristics and other part with randomized controlled solutions, improve the optimization process performance.

C) Diversity criterion: The population must be different during the optimization process. Between each individual of the population must exist a minimum separation distance to ensure heterogeneity in the population. This approach ensures a better exploration of the space of solutions and prevents premature convergence.

D) Selection operator: In the GACB, the selection criterion is performed by the tournament selection method. In two games, the algorithm chooses k topologies (or individuals) randomly and the winning topology is that whose objective function is the best. After the process, there are two parents for crossover phase.

E) Crossover operator: in this paper the single-point crossover is used. For this approach, a number p is selected randomly between one and the complete number of right-of-ways less one. In the example of the Fig. 2 is selected a number between 1 and 5. Then, to conform the descendant, is taken the first p positions from the first parent and the last (n-p) positions from the second parent, where n is the number of right-of-ways. Finally, because each transmission line has a conductor type k, the conductor type always accompanies the transmission line in the swap process.

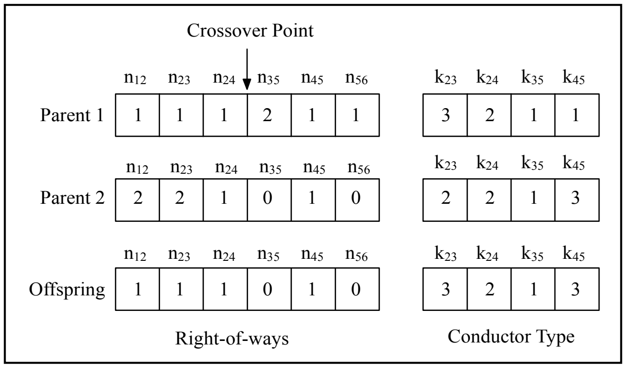

Fig. 2. Proposed crossover criterion in the methodology.

F) Mutation criterion: the Mutation criterion affects the descendant, and it is an alteration in one or more bits in the codification vector according to mutation rate. For the planning problem, the implemented strategy is as follows: a maximum limit of load shedding is defined (*maxcor*). If the proposed descendant has a higher load shedding than the limit imposed, it is given more priority to add circuits in a probabilistically way. In other case, it is given more priority to remove circuits. Also, the strategy has the ability to mutate the k_{ij} conductor type randomly. In Fig. 3 an example is shown.

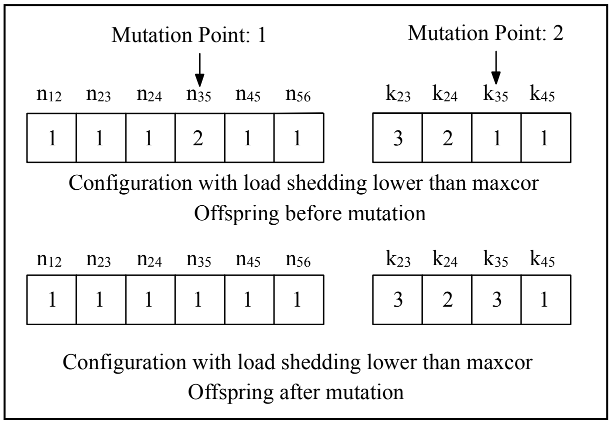

Fig. 3. Proposed mutation criterion in the methodology.

G) Local improvement: the offspring may be subjected to special analysis where its objective function can be improved, or its infeasibility can decrease. In this work, two improvement stages were used. The first stage uses sensitivity analysis. For this purpose, a constructive heuristic technique based on the proposal of Villasana-Garver-Salon was used [17]. The sensitivity indicator identifies interesting additions of circuits that improve the solution. The second stage is based on the identification of irrelevant circuits; circuits that can be eliminated, and as a result, a lower cost in investment is obtained ensuring not to altering the feasibility. To determine the irrelevant circuits, these are ranked in decreasing order based on their investment costs, and only it is considered withdrawing one circuit every time.

H) Population Substitution: In the final stage, the offspring must be different from all members of population. The offspring can replace an individual of the current population in the following cases: 1) the offspring is unfeasible, and in the population exist individuals with worst quality; 2) the offspring is feasible, and in the population exist unfeasible individuals. In the two previous cases, the offspring replaces the worst infeasible individual in the population; 3) the offspring is feasible, and in the population all the individuals are feasible. In this case, the offspring replaces the individual in the population with worst fitness function, only if the offspring has better fitness function than the worst individual.

V. TEST AND RESULTS

The Colombian electric system of 93 buses and 155 candidate lines is used as reference. Like a different alternative of investment to traditional ACSR conductors, ACSS type conductors are proposed in the new transmission lines. There is only one conductor type proposed, but more types can be considered. The circuits presented in base topology of the tests system can be found in [11]. From the base case system, it is proposed ACSS conductors types for the new transmission lines in the currently voltage levels (230 kV and 500 kV). The data associated with the ACSS conductors can be found with the authors. The transmission network expansion planning problem is solved by the proposed methodology in a computer program developed in FORTRAN. On the other hand, the typical conductors in Colombia for the transmission network are the ACSR conductors, close to 80%, and AAAC (All Aluminum Alloy Conductor), close to 8%, [18]. In [19] can be found that the cost of ACSR and AAAC conductors are similar for equivalent diameter. In this work, a sensitivity analysis in the cost of the ACSS conductor is realized. The planning problem is solved considering a variable cost between 1.1-1.5 times respect to conventional ACSR cost. Then, respect to ACSS conductor power flow capacity in relation to ACSR, for the 230 kV voltage level the increase in capacity is approximately 84%; and for the 500 kV voltage level the increase is approximately 80%. However, in this study, it is taken a security factor to limit the power transport capacity to 69% and 65% for the 230kV and 500kV voltage levels, respectly (sf=0.92).

Solution of the traditional Colombian system: In this work, it is taken as reference the optimal solution of US$ 560.002 x10^6 with a load shedding of 0.38 MW [20]. The above solution is given by the traditional planning and proposes the following additions:

n_{43-88}=2, n_{15-18} =1, n_{30-65} =1, n_{30-72} =1, n_{55-57} =1, n_{55-84} =1, n_{56-57} =1, n_{55-62} =1, n_{27-29} =1, n_{29-64} =1, n_{50-54}=1, n_{62-73}=1, n_{54-56}=1, n_{72-73}=1, n_{19-82}=2, n_{82-85}= 1, y n_{68-86}=1.

In the above solution, n_{ij} is the number of circuits added in the *i-j* branch for the network. In this case, the codification determines the circuits that must be added to the network and does not include the conductor type. The GACB finds the solution in an average of 19000 LPs.

Colombian system with ACSS proposals: The sensitivity analysis is done considering that the cost of ACSS conductor is: 1.1, 1.3, and 1.5 times the cost of a conventional circuit. The optimal solution that is found in the three cases is formed by the same circuits, but its costs are different. When the cost is 1.1 times the solution is US$ 506.79 x 10^6. In the case 1.3 times the cost is US$ 512.702 x 10^6; and in the case 1.5 times the cost is $US 518.609 x 10^6. The load shedding in the three solutions is 0.39 MW and the proposed topology is as follows:

n_{15-18} =1, n_{30-65} =1, n_{30-72} =1, n_{55-57} =1, n_{55-84} =1, n_{55-62} =1, n_{27-29} =1, n_{29-64} =1, n_{62-73} =1, n_{45-81} =1, n_{72-73} =1, n_{19-82} =2, n_{82-85}=1, n_{68-86} =1, $n_{43-88/ACSS}$ =1, $n_{57-81/ACSS}$ =1.

In this solution, n_{ij} is the number of ACSR type circuits added in the *i-j* branch and $n_{ij/\mathrm{ACSS}}$ represents the circuits added in the *i-j* branch in the ACSS type. The proposed topology with ACSS conductors improves the traditional optimal solution. The methodology of solution uses an initial population formed by some solutions created using constructive heuristic algorithms [16, 17]. The parameters used in the GACB are as follows: mutation rate between 3 and 5 %; population size between 10 and 40 chromosomes; a diversity factor of 1 gene of difference. Suboptimal solutions obtained using the GACB with a few generations are inserted in the initial population to improve the algorithm performance. The GACB found the solutions in an average of 86000 LPs.

In the particular case of the Colombian electricity system, the suggested methodology replaces the two proposed circuits in the right-of-way {88-43}, obtained with the traditional planning, by a single circuit of ACSS type. On the other hand, it is observed that the suggested methodology replaces the complete transmission path {57-56; 54-56; 50-54}, by a single circuit of ACSS type in the transmission line {57-81}, and a single addition of the conventional type in the transmission line {45-81}. Importantly, the rest of the solution remains the same. With this modification, the investment cost goes from U.S. $ 560.002 x 10^6 until U.S. $ 506.79 x 10^6 in the best case, i.e., a cost reduction of about 9.5% is produced. The proposed methodology can be modified to consider HTLS conductors in the existing transmission lines through only replacing the conductor in the network. This idea changed the traditional concept of preserving all elements in the existing currently network in the optimal future solution. In this way, it would be possible to have an option that links up maintenance and planning, because if an existing conductor is changed, the lifespan of the right-of-way is extended. On the other hand, this work does not include technical analysis of electrical losses. The aspects related above will be analyzed in future researches.

VI. CONCLUSION

When the conductor type of the transmission lines is considered as a decision variable of the transmission expansion problem, and in particular when is considered HTLS conductors, it is observed a profit in the investment cost. The profit is relative to optimal solution that is found in the traditional transmission planning problem.

When it is considering options for conductor type, the space of solutions is significantly increased. Finally a solution of lower cost but with a greater computational effort is obtained.

To determine whether or not it is interesting replacing conventional conductors by HTLS conductors, it is necessary to use optimization methods to perform a thorough exploration in the space of solutions. This because in the optimization process, the solutions are topologically different and they have higher quality than the solutions obtained with traditional planning that do not consider the use of HTLS conductors.

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